

BULGE GLOBULAR CLUSTERS IN SPIRAL GALAXIES

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ABSTRACT

There is now strong evidence that the metal-rich globular clusters (GC) near the center of our Galaxy are associated with the Galactic bulge rather than the disk as previously thought. Here we extend the concept of bulge GCs to the GC systems of nearby spiral galaxies. In particular, the kinematic and metallicity properties of the GC systems favor a bulge rather than a disk origin. The number of metal-rich GCs normalized by the bulge luminosity is roughly constant (i.e. bulge $S_N \sim 1$) in nearby spirals, and this value is similar to that for field ellipticals when only the red (metal-rich) GCs are considered. We argue that the metallicity distributions of GCs in spiral and elliptical galaxies are remarkably similar, and that they obey the same correlation of mean GC metallicity with host galaxy mass. We further suggest that the metal-rich GCs in spirals are the direct analogs of the red GCs seen in ellipticals. The formation of a bulge/spheroidal stellar system is accompanied by the formation of metal-rich GCs. The similarities between GC systems in spiral and elliptical galaxies appear to be greater than the differences.

Subject headings: galaxies: formation — galaxies: individual (M31, M81, M104) — galaxies: star clusters.

1. INTRODUCTION

Globular clusters (GCs) in our Galaxy can be broadly divided into two classes on the basis of their metallicity and/or kinematics (e.g. Zinn 1985). The metal-poor, non-rotating subpopulation has long been associated with the Galaxy halo. The metal-rich GC system reveals significant rotation and has historically been associated with the disk. Following early suggestions by Harris (1976), a view is now emerging that metal-rich GCs within ~ 5 kpc of the Milky Way galactic center are associated with the bulge rather than the disk (Frenk & White 1982; Minniti 1995; Cote 1999). Specifically, the central metal-rich GCs are spherically distributed about the galaxy center and overlap in metallicity with the bulge field stars. In terms of kinematics, the GCs have a similar velocity dispersion and reveal solid body rotation matching that of the bulge stars. Beyond ~ 5 kpc the metal-rich GCs have properties consistent with the thick disk component. The GCs also appear to be coeval with the bulge stars (Ortolani *et al.* 1995). Cote *et al.* (2000) has successfully modelled the Galactic GC system based on hierarchical build-up around a protobulge and its metal-rich GCs.

Here we extend this view of ‘bulge GCs’ to other spiral galaxies. In particular, we suggest that the inner metal-rich GCs in M31, M81 and M104 spiral galaxies are associated with their bulges. We further suggest that the red (metal-rich) GC subpopulations in giant ellipticals are their analogs, in agreement with the view advocated by Cote *et al.* (2000). Thus the bulges of spirals, S0s and the entire stellar component of ellipticals (which we collectively refer to as the ‘bulge’) may all have associated metal-rich GCs. We briefly discuss the implications for GC and galaxy formation.

2. BULGE GLOBULAR CLUSTER KINEMATICS

2.1. M31

The Andromeda galaxy (M31; Sb) reveals a bimodal GC metallicity distribution with the metal-rich GCs preferentially close to the galaxy center (e.g. Huchra, Kent & Brodie 1991). Based on their kinematics, Huchra *et al.* concluded that interior to ~ 2 kpc the metal-rich GCs were rapidly rotating. Recently Perrett *et al.* (2001) have obtained velocities for over 200 GCs in the M31 system. They find a velocity dispersion of 146 ± 12 km/s. This is consistent with the central *stellar* velocity dispersion of 150 km/s (van den Bergh 1999). Furthermore the metal-rich GCs reveal solid-body-like rotation within 5 kpc with an amplitude similar to that of the stellar rotation curve which is dominated by the bulge at these small radii (e.g. Rubin & Ford 1970). They also find that the metal-rich GC system is spherically distributed about the galaxy center. Thus, the inner metal-rich GCs in M31 reveal the same features that have lead previous workers to associate equivalent GCs in our Galaxy with the bulge.

2.2. M81

The GC system of M81 (Sa/Sb) is less well studied than M31 but both photometric (Perelmuter & Racine 1995) and kinematic studies (Perelmuter, Brodie & Huchra 1995; Schroder *et al.* 2001) have noted similarities to the Milky Way’s GC system. Schroder *et al.* (2001) give the kinematics for the metal-rich GCs within 2 kpc of the galaxy center from Keck spectra. They derive a velocity dispersion of 152 ± 36 km/s and rotation velocity of 96 ± 56 km/s. Measurements of the *stellar* central velocity dispersion vary from 150 to 180 km/s with a median value of 167 km/s. The *stellar* rotation curve for M81 peaks at around

0.5 kpc radius with a value of ~ 110 km/s (Heraudeau & Simien 1998). The stellar values are slightly higher than those inferred for the GC system, but are well within the errors. Although the evidence is less strong, the inner metal-rich GCs of M81 have kinematic properties that are consistent with the bulge.

3. GLOBULAR CLUSTER METALLICITIES

Individual metallicities are now available for over 250 GCs in M31 (Barmby *et al.* 2000). For M81, the photometry of Perelmuter & Racine (1995) was insufficient to clearly differentiate the metal-poor and metal-rich subpopulations but they did note that the inner GC sample was dominated by red (metal-rich) objects. Perhaps the best photometrically-studied GC system in a spiral galaxy beyond the Local Group is that of the Sombrero galaxy (M104; Sa). The recent HST imaging study of Larsen, Forbes & Brodie (2001) showed that the GC system has two distinct subpopulations. After Galactic extinction correction and color transformation using Kissler-Patig *et al.* (1998), we show in Fig. 1 the metallicity distribution of GCs in M104 compared to that of M31, the Milky Way and M33 (data from Forbes *et al.* 2000). If we consider a cut at say $[\text{Fe}/\text{H}] = -1$, then it is clear that the ratio of metal-rich to metal-poor GCs is significantly higher in M104 than the other spirals. Since M104 has a tiny disk and a dominant bulge it is tempting to associate the metal-rich GCs with the bulge rather than the disk component (see also Section 4). If the samples are restricted to the GCs to within 5 kpc of the galaxy center then the situation is even more pronounced.

M33 (Sc) at the opposite extreme has very few GCs with $[\text{Fe}/\text{H}] > -1$. Its ‘bulge’ has a luminosity of $M_V \sim -15$ (Bothun 1992). Local Group dwarf galaxies of this luminosity, typically have less than half a dozen GCs. Thus if the M33 bulge is analogous to a small galaxy few associated GCs are expected. We note that the LMC (another bulgeless galaxy) also lacks metal-rich GCs. For M31 (Sb) and the Milky Way (Sbc) the number of metal-rich GCs (relative to metal-poor ones) is intermediate between M104 (Sa) and M33 (Sc). We note that Kissler-Patig *et al.* (1997) associate the red GCs in the S0 galaxy NGC 1380 with that galaxy’s bulge. *It seems likely that the relative number of metal-rich GCs is related to the host galaxy Hubble type and hence the relative importance of a galaxy’s bulge.*

How are the metal-rich and metal-poor subpopulations in spiral galaxies related to those seen in early type galaxies? Historically, one difference between the GC metallicity distributions in spirals and ellipticals were thought to be the mean metallicity of the two peaks. M104, M31 and the Milky Way all have GC subpopulations with mean metallicities of $[\text{Fe}/\text{H}] \sim -1.5$ and -0.5 (see Fig. 1) while ellipticals were thought to have GC mean values of $[\text{Fe}/\text{H}] \sim -1.0$ and 0.0 (Harris 1991). Recently, two developments have caused us to reassess the mean GC metallicity in ellipticals towards lower metallicities. The first effect is the use of more accurate transformations from optical colors to $[\text{Fe}/\text{H}]$. For example, the new transformation of Kissler-Patig *et al.* (1998) converts a typical $V-I = 1.05$ to $[\text{Fe}/\text{H}] = -1.07$, where the old Galactic-based transforma-

tion would give $[\text{Fe}/\text{H}] \sim -0.5$ (Couture *et al.* 1990). The second effect is that the more accurate Galactic extinction values of Schlegel *et al.* (1998) tend to be larger on average by up to $A_V \sim 0.1$, than the traditionally-used Burstein & Heiles (1984) values. Thus extinction-corrected GC colors are now bluer than before, and more metal-poor when transformed. If these two effects are taken into account, the two GC subpopulations in ellipticals have mean metallicities of $[\text{Fe}/\text{H}] \sim -1.5$ and -0.5 which is similar to those in spirals. *To first order there appears to be very little difference between the mean metallicity of the two subpopulations in late and early-type galaxies.*

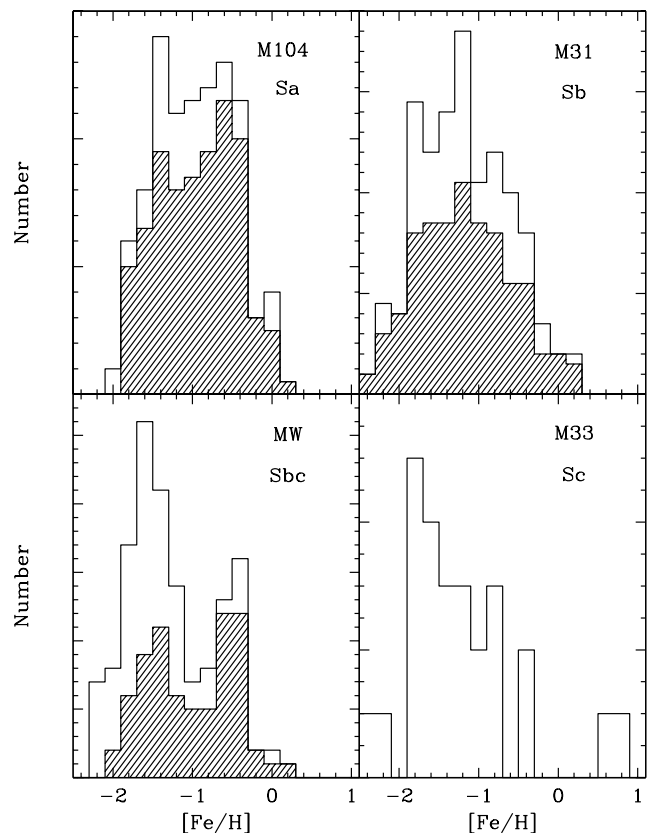


FIG. 1.— Metallicity distributions of GCs in M104, M31, Milky Way and M33. The y axis has been scaled arbitrarily. Open histograms show the total GC population observed, and hashed histograms show GCs with 5 kpc of the galactic center (except for M33). M104 has more metal-rich (e.g. $[\text{Fe}/\text{H}] > -1$) to metal-poor GCs than the later type spirals.

When GC metallicities are examined in still more detail, it is found that the mean GC color (metallicity) correlates with galaxy velocity dispersion for *early-type* galaxies (Forbes & Forte 2001; Larsen *et al.* 2001). Do the bulge GCs of spirals follow the same relation as early-type galaxies?

We have collected a sample of 37 early-type galaxies from the literature with bimodal GC color distributions. The mean color of the metal-rich subpopulation has been corrected to a common $V-I$ color (Forbes & Forte 2001) and corrected for extinction using Schlegel *et al.* (1998).

To this sample we add M104, M31 and the Milky Way GC systems (the combined sample data are available at <http://astronomy.swin.edu.au/staff/dforbes/glob.html>). The V-I color of the M31 and Milky Way metal-rich GCs have been calculated using the transformations of Barmby *et al.* (2000). Central velocity dispersions come from Gebhardt *et al.* (2000) and Kent (1992). The uncertainty in the mean color is rarely quoted in the original works. We have decided to adopt relatively conservative error estimates (i.e. $\pm 0.03^m$ for HST data with definite bimodality, ± 0.05 for probable bimodality and ± 0.08 for ground-based data to reflect the higher photometric errors and contamination rates). They may be smaller than we assume since the scatter in the data points is generally less than the errors. This means that we will tend to underestimate the significance of any slope compared to the error on the slope from a least-squares fit.

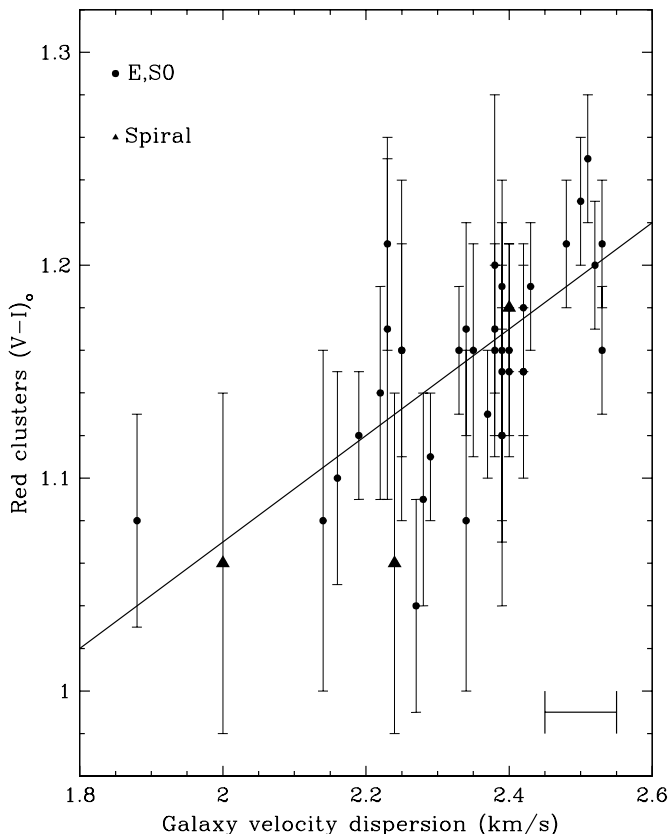


FIG. 2.— Mean color of the red (metal-rich) globular cluster subpopulations versus log galaxy velocity dispersion. Early-type galaxies are shown by filled circles and spirals by triangles. A typical velocity dispersion error is shown in the lower left. The solid line shows the best fit to the early-type galaxies (slope = 0.26 ± 0.06 , intercept = 0.56 ± 0.14). The correlation is significant at the 4σ level. The three spiral galaxies (MW, M31, M104) are consistent with the overall early-type galaxy relation.

The data are shown in Fig. 2. For the early-type galaxies, the Spearman rank correlation indicates that the red GCs are correlated with galaxy velocity dispersion with a probability of 99.9%. A least squares fit gives a positive

slope (similar to that found by Forbes & Forte (2001) and Larsen *et al.* (2001) for smaller samples) at the 4σ level. The mean colors of the metal-rich GC subpopulations in the three spirals are also plotted in Fig. 2. *The red GCs in spirals are consistent with the metallicity – velocity dispersion relation for early-type galaxies.*

If we use only the high quality sample (i.e. HST data with definite bimodality) then the Spearman test gives 99.5% and a slope of 4σ . An unweighted fit to the high quality sample gives a similar slope, with slightly increased significance of 5σ .

4. BULGE SPECIFIC FREQUENCY

Traditionally GC specific frequency S_N refers to the total number of GCs per galaxy luminosity, normalised to $M_V = -15$. Harris (1981) was the first to compare *total* GC numbers in spirals with the luminosity of the bulge component. Recently, Cote *et al.* (2000) pointed out that S_N defined in this manner was indistinguishable for spirals and ellipticals in similar environments. Here we focus on the metal-rich/red GCs in spirals/ellipticals, compared to the bulge luminosity (we assume that ellipticals are bulge dominated systems). We refer to this as the bulge S_N .

The total number of GCs and the number of metal-rich GCs are given by Larsen, Forbes & Brodie (2000) for M104, and in the compilation of Forbes *et al.* (2000) for M31 and the Milky Way. These numbers and the host galaxy magnitudes discussed below are summarized in Table 1. From the galaxy total magnitudes, we calculate the bulge and disk magnitudes using the following method. The bulge-to-total (B/T) luminosity for M104 has been given by Kent (1988) as 0.85 and by Baggett *et al.* (1998) as 0.73. Here we use 0.8. For M31 (Sb) and the MW (Sbc) we use the B/T variations with Hubble type of Simien & de Vaucouleurs (1986), i.e. $B/T = 0.25$ and $B/T = 0.19$ respectively with a dispersion of about ± 0.05 within a given Hubble type. For the disk contribution we assume that the halo light is negligible and hence all of the remaining light comes from the disk.

In Section 2 we argued, mostly from the kinematic data, that the bulk of metal-rich GCs in spirals are not associated with the disk but rather the bulge component. Further support for this idea comes from examining the number of metal-rich GCs per unit starlight. The GC system of M104 provides a key data point. For M104 the total number of red GCs and the disk magnitude combine to give a disk S_N of 4.4 ± 5.2 . Assuming that the disks in M31 and the Milky Way have similar stellar populations (i.e. M/L), the disk S_N of M104 is about 20 times that of these other spirals. This large variation in disk S_N suggests that the bulk of metal-rich GCs in spirals are not in fact disk objects.

From the bulge magnitudes and number of metal-rich GCs given above, we derive bulge S_N values of 1.1 ± 0.8 (M104), 0.6 ± 0.3 (M31) and 0.8 ± 0.9 (MW). Unlike the disk S_N values, bulge S_N values are fairly consistent between the three spirals.

In the case of the Milky Way only GCs within ~ 5 kpc show bulge characteristics while those further out have been associated with the thick disk (Minniti 1995; Cote 1999). In terms of the bulge effective radius, 5 kpc is $2 R_{eff}$ (van den Bergh 1999). The bulge effective radii

for M104 and M31 are 8 kpc (Bender, Burstein & Faber 1992) and 2.5 kpc (van den Bergh 1999) respectively. If the metal-rich GC samples in M104 and M31 are restricted to within $2 R_{eff}$, then we estimate about 378 metal-rich GCs in M104 (from Larsen, Forbes & Brodie 2001) and 61 in M31 (from Barmby *et al.* 2000). The Milky Way has about 35 known metal-rich GCs within $2 R_{eff}$. Thus the bulge S_N values within $2 R_{eff}$ are 0.6 ± 0.5 , 0.4 ± 0.2 and 0.6 ± 0.6 for M104, M31 and the Milky Way respectively. Within the errors, the bulge S_N values for M104, M31 and the Milky Way are consistent. *So although the three spirals span a range of Hubble types from Sa to Sbc, the bulge S_N appears to be nearly constant for spiral galaxies.*

In each case, there is a tendency to miss some metal-rich GCs as they are harder to detect near galaxy centers. For example, about a dozen GCs are thought to be hidden from our view in the Milky Way (van den Bergh 1999). Recently the 2MASS survey has detected two more metal-rich bulge GCs (Hurt *et al.* 2000). Barmby *et al.* (2000) give photometry for about 2/3 of the total GC population in M31 which has an estimated total population of 400 ± 55 . Again many of the missing GCs will be associated with the bulge. The derived bulge S_N values may be underestimated by up to 30%.

How do the bulge S_N values for spirals compare to ellipticals? Field ellipticals have *total* S_N values of 1–3 (Harris 1991). The fraction of red GCs in ellipticals is typically about half (e.g. Forbes, Brodie & Grillmair 1997). For example, wide area studies of the field/group ellipticals NGC 1052 and NGC 1700 found red fractions and total S_N values of 0.50, 1.7 and 0.56, 1.3 respectively (Forbes, Georgakakis & Brodie 2001; Brown *et al.* 2000). This implies that field ellipticals typically have *bulge* S_N values of 0.5–1.5. *Thus field ellipticals have similar bulge S_N values to field spirals.* This provides further support for our claim that the metal-rich GCs in spirals and those in ellipticals have the same origin, i.e. they formed along with the bulge stars. We note that cluster ellipticals may have similar S_N values when the mass of hot gas is taken into account (McLaughlin 1999). Little is known about the GC systems of cluster spirals.

5. CONCLUDING REMARKS

From globular cluster (GC) kinematic information we have argued that the inner, metal-rich GCs in the nearby spirals M31 and M81 have a bulge origin. On the basis of GC numbers and specific frequency, we showed that the metal-rich GCs in the Sa spiral M104 are most likely associated with the dominant bulge rather than the small disk component. The derived bulge specific frequency for the GCs in M104, M31 and the Milky Way are consistent with a constant value of ~ 1 . This is similar to the value for field ellipticals (when only the metal-rich GCs are considered) but is less than that for cluster ellipticals. The metallicity distributions of GCs in late and early-type galaxies are similar to first order, and obey the same correlation of mean GC metallicity with host galaxy velocity dispersion. This relation, indicates a common chemical enrichment history for the metal-rich GCs and the host galaxy (Forbes & Forte 2001).

We conclude that the majority of the metal-rich GCs in spirals are associated with the galaxy bulge, and that these GCs are the analogs of the red (metal-rich) GCs in giant ellipticals. Thus GC systems provide another example of the similarity between ellipticals and spiral bulges (e.g. Wyse, Gilmore & Franx 1997). By extension this would suggest that bulges and ellipticals formed by a similar mechanism. In the case of the Milky Way bulge, van den Bergh (1996) concluded that it was formed by a rapid but clumpy collapse.

In the multi-phase collapse model for GC formation proposed by Forbes, Brodie & Grillmair (1997) the ‘bulge’ of a giant elliptical galaxy occurred in the second or galactic phase. The red GCs formed during this phase. In that paper, we associated the metal-rich GCs of spirals with disks and speculated that they were a third phase of GC formation. It now seems likely that the bulk of metal-rich GCs in spirals were formed along with the bulge stars and it is these that are directly analogous to red GCs in giant ellipticals.

6. ACKNOWLEDGMENTS

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TABLE 1
 GLOBULAR CLUSTER BULGE SPECIFIC FREQUENCY

	M104	M31	Milky Way
Globular cluster total	1150±575	400±55	160±20
Metal-rich clusters (all radii)	667±333	100±14	53±7
Metal-rich clusters ($<2R_{eff}$)	378±189	61±8	35±4
Galaxy total M_V	-22.2±0.1	-22.0±0.2	-21.3±0.3
Bulge-to-total ratio	0.80±0.05	0.25±0.05	0.19±0.05
Disk S_N (all radii)	4.4±5.2	0.2±0.1	0.2±0.1
Bulge S_N (all radii)	1.1±0.8	0.6±0.3	0.8±0.9
Bulge S_N ($<2R_{eff}$)	0.6±0.5	0.4±0.2	0.6±0.6

^aThe table lists the total number of globular clusters, the metal-rich subpopulation and those within twice the bulge R_{eff} . The bulge and disk specific frequencies, S_N , use bulge and disk luminosities respectively.